The original publication is available www.springer.com.
DOI: 10.1007/s10055-011-0192-z

Noname manuscript No.
(will be inserted by the editor)

Discriminability-Based Evaluation of Transmission Capability of Tactile Transmission Systems

Shogo Okamoto · Masashi Konyo · Satoshi Tadokoro

Received: date / Accepted: date

Abstract Tactile transmission systems deliver tactile information such as texture roughness to operators of robotic systems. Such systems are typically composed of tactile sensors that sense the physical characteristics of textures and tactile displays that present tactile stimuli to operators. One problem associated with tactile transmission systems is that when the system has a bottleneck, it is difficult to identify whether the tactile sensor, tactile display, or perceptual ability of the user is the cause because they have different performance criteria. To solve this problem, this study established an evaluation method that uses the discriminability index as an evaluation criterion. The method lets tactile sensors, displays, and human tactile perception be assessed in terms of the ability to transmit physical quantities; the same criterion is used for all three possible causes so that their abilities can be directly compared. The developed method was applied to a tactile-roughness transmission system (Okamoto et al. 2009), and its tactile sensor was identified as the bottleneck of the system.

Keywords Assessment of man-machine system · Discriminability index · Performance measurement · Tactile display · Tactile sensor

1 Introduction

A large number of tele-operation or telecommunication systems provide sensory feedback to users; these can include force, tactile, or visual sensations. Sensory feedback is useful for improving the operability and validity of such systems. Quantitatively evaluating the components of sensory-feedback systems and identifying the components that cause deterioration in the system performance will be useful for enhancing sensory feedback.

S. Okamoto
The Graduate School of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Japan
E-mail: okamoto-shogo@mech.nagoya-u.ac.jp

M. Konyo and S. Tadokoro
The Graduate School of Information Sciences, Tohoku University, 6-6-1, Aramaki Aza Aoba, Sendai, Japan

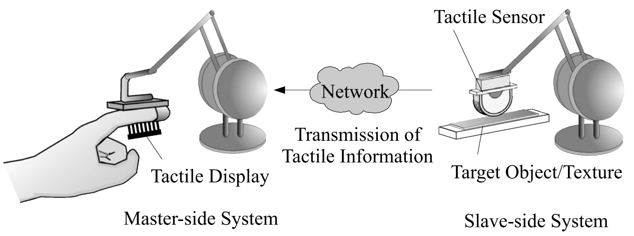

Fig. 1 Image of Master-Slave-Type Tactile Transmission System

This study focuses on tactile transmission systems, which are a type of sensory feedback system. Tactile transmission systems deal with cutaneous sensations such as the texture sensations of rough or smooth surfaces and the sense of contact with objects. Several tactile transmission systems have been developed thus far. Most of these systems consist of tactile sensors and displays. For instance, consider the transmission of texture sensations in systems using master-slave-type robots (Fig. 1). In such systems, tactile sensors and displays are installed in slave and master robots, respectively. The sensation of the textures touched by the slave robot is transmitted to the operator by means of tactile displays (Yamauchi et al. 2010; Yamamoto et al. 2006). In palpation systems used for minimally invasive surgery, tactile sensors have been installed on the tip of probes. The probes are pressed onto the body tissues of patients. Tactile displays equipped on the other side of the probe provide physicians with information on the pressure distribution on the tactile sensor (Ottermo 2006;

Howe et al. 1995). For prostheses, information on contact locations or the intensity of force applied to artificial limbs is delivered to the wearers (Fan et al. 2008; Warwick et al. 2003).

Problems The accuracy of the tactile sensations delivered to the operators or users depends on the tactile sensor's ability to sense texture or contact information, tactile display's ability to present tactile stimuli to the operators, and operator's perceptual ability. If the performance of the developed tactile transmission systems is found to be worse than what is required or expected, the bottleneck in the system causing the deterioration in performance must be identified and corrected. However, no method has yet been established that quantitatively compares the performance of the tactile display, sensor, and human perception individually and holistically and then correctly identifies the factors causing the deterioration.

If tactile sensors with sensing abilities considerably better than those of humans are available, and if tactile displays are capable of presenting stimuli with resolutions better than what a human can distinguish, quantitatively comparing the abilities of the display, sensor, and human tactile perception would be unnecessary. In such cases, the human perceptual capability would limit the performance of the entire system. However, human tactile perception has good resolution and a wide sensible range both spatially and temporally. For example, a human finger can detect vibratory stimuli with an amplitude of smaller than 1 μm and a weight of less than 0.1 g to the pain level of a few kilograms, discriminate two-point stimuli with a gap of approximately 2 mm, and respond to vibrations of 1 kHz (Jones et al. 2006). Of course, some devices partially surpass these sensitivity levels. For example, Motoo et al. (2007) developed a tactile sensor with a sensitivity range that changes from the level of a few Pascals to 10 kPa. Summers et al. (2002) developed a tactile pin matrix display with 100 independently drivable pins in an area of 1 cm^2. Killebrew et al. (2007) devised a dense matrix with 400 pins/cm^2 for neurophysiological purposes. However, in general, it is technically difficult to develop tactile sensors and displays with abilities that surpass human tactile perception. Further, manufacturers of commercial products usually do not prefer systems in which some components perform considerably better than others. Therefore, in most tactile transmission systems, tactile sensors and displays whose abilities more or less match humans tactile perception are used. These components of a tactile transmission system must be quantitatively compared in order to identify the bottleneck among them.

Objective The objective of this study is to establish an evaluation method that can assess tactile sensors, displays, and human tactile perception using the same criterion and thus identify the bottlenecks in a tactile transmission system. As an example, the proposed method is applied to a roughness transmission system.

2 Related Studies

This section describes the manner in which tactile transmission systems were evaluated in related studies. The tactile sensor and tactile display are chosen or developed before the development of the transmission system. In previous studies, tactile sensors were designed on the basis of certain criteria such as spatial resolution, maximal and minimal sensible pressure, and refresh rate (Ottermo 2006; Pawluk et al. 1998). Similarly, tactile displays were designed on the basis of spatial density, maximal output force or displacement, and frequency response characteristics of tactors (Goethals et al. 2008; Peine et al. 1997; Yao & Hayward 2005).

For completely developed and ready systems, the performance of the entire system was evaluated in previous studies in terms of how operators actually use the systems and perform tasks. For example, when evaluating texture transmission systems, operators select the textures that they feel are closest to those perceived through the system (Yamamoto et al. 2006). In some studies, the performance of palpation systems with tactile transmissions was evaluated by performing tasks to distinguish the size and stiffness of tumor-like objects (Ottermo 2006) or to localize them (Howe et al. 1995). The performance of prostheses with tactile feedback was evaluated through tasks in which the wearers discriminate the intensity or pattern of pressure stimuli that are presented to the limbs (Fan et al. 2008). For teleoperation systems with tactile feedback, one study rated the performance of the systems on the basis of the completion time of given tasks, such as putting a peg into a hole (Kontarinis & Howe 1995). Subjective ratings in accordance with the Likert scale or quality of service have also been employed to evaluate the validity of sensory feedback systems (Dev et al. 2002; Hikichi et al. 2006). Some of these subjective assessments come from the standards devised by the International Telecommunication Union for assessing pictures and sounds (ITU-R 2004; ITU-R 2009).

When tactile transmission systems are developed, the sensor and display are designed first; the system is then constructed from the components. Finally, the performance of the entire system is comprehensively evaluated through experimental tasks. However, the primary objective of the abovementioned studies was to test the effectiveness of the developed tactile transmission systems and not to achieve a quantitative comparison of the components for identifying bottlenecks in the system.

3 Proposed Method

Three conditions were considered for evaluation in the proposed method. First, the same criteria must be applied to the tactile sensor, tactile display, human perception, and the entire system. Second, the method must evaluate the transmission capabilities for physical quantities because many tactile transmission systems sense physical quantities and represent them to the users. Finally, considering the noise in sensory outputs and the variations in human responses to a stimulus, the evaluation method should be applicable to systems with probabilistic responses.

This paper proposes the adoption of discriminability indices for physical quantities as the evaluation criteria; these are applied to the tactile sensor, tactile display, human tactile perception, and the entire system. The discriminability index is an index that is used in signal detection theory to indicate how readily a human can detect stimuli (Green & Swets 1966).The indices are calculated by observing the variations in human responses toward physical stimuli. Because the discriminability index assumes that the responses toward the stimuli follow probabilistic distribution, it can be used for both human perception as well as tactile sensory systems. The index allows us to evaluate and compare each component of tactile transmission systems using the same criteria.

The method evaluates the system based on the accuracy when transferring a unique physical quantity. Therefore, the proposed method is not effective for tactile information involving multiple physical quantities. For instance, the recognition of textures, i.e., clothes, is affected by the various physical properties of textures. Hence, the proposed method cannot evaluate how accurately the texture sensations are transferred. However, it can be applied to each of the physical properties that are related to texture sensations, such as surface roughness or friction coefficient. In this case, the method can be effectively applied to those physical quantities that predominately contribute to the texture sensations. These physical quantities have been identified to some extent (e.g., Shirado et al. 2005; Yoshioka et al. 2007).

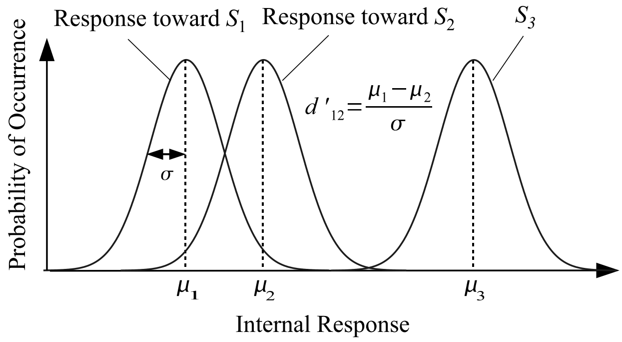

Fig. 2 Human Probabilistic Response toward Physical Stimuli

3.1 Discriminability Index

In signal detection theory, d' is used as the discriminability index and is calculated from the distributions of a human's response toward physical stimuli. Fig. 2 shows the distributions of internal responses of a human to three physical stimuli S_1, S_2, and S_3. These physical stimuli have different magnitudes. The human responses to these stimuli follow the normal distributions with averages of μ_1, μ_2, and μ_3, respectively, and the standard deviations of σ. The definition for d' is determined by the distance between the centers of two internal responses and the uncertainty σ, which is given by

$$d'_{ij} = \frac{\mu_i - \mu_j}{\sigma}. \quad (1)$$

A large d' value indicates that it is easy to detect the difference between S_i and S_j. When perceptual unidimensionality can be expected,

$$d'_{13} = d'_{12} + d'_{23} \quad (2)$$

holds (Macmillan & Creelman 2005). d'_{13} is also given by

$$d'_{13} = \frac{\mu_1 - \mu_3}{\sigma}. \quad (3)$$

However, for real experimental data, the cumulative d'_{13} determined by (2) is not always equal to the one derived by (3). Hence, in this study, we use the estimated d' determined by the least square method (Gulliksen 1956) using the d' values of (2) and (3).

Let d'_{ij} be d' between S_i and S_j $(i, j = 1, ..., n)$. d'_{0i} is the estimated d' between S_i and an arbitrary origin of the internal response. The observed d'_{ij} is described by the estimated d'_{0i} and d'_{0j}:

$$d'_{ij} = -d'_{0i} + d'_{0j}. \quad (4)$$

Therefore,

$$\sum_{j=1}^{n} d'_{ij} = -(n-1) \cdot d'_{0i} + \sum_{j=1}^{n} d'_{0j} \quad i \neq j. \quad (5)$$

Because we have (5) for each i, we get

$$\begin{bmatrix} \sum_{j=1}^{n} d'_{1j} \\ \vdots \\ \sum_{j=1}^{n} d'_{nj} \end{bmatrix} = \begin{bmatrix} -(n-1) & \cdots & 1 \\ \vdots & \ddots & \vdots \\ 1 & \cdots & -(n-1) \end{bmatrix} \begin{bmatrix} d'_{01} \\ \vdots \\ d'_{0n} \end{bmatrix}. \quad (6)$$

We describe (6) as

$$D_{obs} = A \cdot D_{est}. \quad (7)$$

However, because of the lack of degrees of freedom, A^{-1} does not exist. To solve this, we need to use a submatrix of A. We assign zero to d'_{01}, which means that we set the origin on d'_{01}. Then, the first column of A is eliminated, and (6) is transformed to

$$\begin{bmatrix} \sum_{j=1}^{n} d'_{1j} \\ \vdots \\ \sum_{j=1}^{n} d'_{nj} \end{bmatrix} = \begin{bmatrix} 1 & \cdots & 1 \\ \vdots & \ddots & \vdots \\ 1 & \cdots & -(n-1) \end{bmatrix} \begin{bmatrix} d'_{02} \\ \vdots \\ d'_{0n} \end{bmatrix}. \quad (8)$$

We describe (8) as

$$D_{obs} = B \cdot E_{est}. \quad (9)$$

The estimated d' values are given by

$$E_{est} = (B^T B)^{-1} B^T D_{obs}. \quad (10)$$

3.2 Procedures of Proposed Evaluation Method

In the evaluation procedure, the performances of the tactile sensor, tactile display, human tactile perception, and the entire system are evaluated by conducting experiments. For each experiment, discriminability indices are computed from the responses of human observers or of tactile sensors. For the tactile display, its outputs for given commands are assessed for computing the indices.

First, the evaluation for the tactile sensor is described. Here, the sensory outputs against the inputs of physical stimuli are recorded; this is a standard assessment procedure for sensors. For example, for signal detection tasks, we record the ratios at which the sensor successfully detects the physical stimuli. The discriminability index is then calculated based on the signal detection ratios. For example, for signal discrimination tasks, sensory outputs with an input of physical stimulus are recorded, and the mean and standard deviations for the outputs of each input are recorded. By applying the law of comparative judgment (Thurstone 1927), which is elaborated upon in section 5.1, to the measured means and standard deviations, the discriminability indices are calculated.

Second, with respect to the evaluation of tactile displays, the display is used repeatedly, and its outputs are recorded. This is a common assessment process for tactile displays. The discriminability indices are computed from the output means and deviations.

To evaluate the human ability for tactile perception, the tactile display is not used, and the physical stimulus is directly applied to the finger of the experiment participants, who may also explore the stimuli using their bare fingers. Because, data on the sensitivity of tactile perception are available in literature in many cases, additional experiments may not be needed.

When real stimulus samples can be used to evaluate human tactile perception or when the usage of such stimuli is appropriate, an evaluation involving real samples is recommended as a straightforward method. For some tactile displays, however, stimuli from tactile displays qualitatively differ from those from the real samples. For example, a plane composed of a pin matrix is different from the continuous surfaces of real samples. In such cases, a comparison between human tactile perception of the stimuli presented by the tactile display and that of real samples is invalid. Therefore, in cases such as the example in section 5, the ability of human tactile perception is evaluated against the stimuli applied by the tactile display. It should be noted that the abilities of human and tactile displays cannot be separately assessed in these cases. In this method, the human responses against physical stimuli presented by a tactile display are recorded. Similarly to for the tactile sensor, both signal detection and discrimination tasks are possible. Signal detection tasks are based on the signal detection ratios, while discrimination tasks are based on the correct discrimination ratios of the task; in both cases, the discriminability index is calculated by taking these factors into consideration.

Finally, to evaluate the entire system, the index is calculated in the same manner as that for the human perception mentioned above. However, in this procedure, the experiments are conducted by using the entire system connecting the tactile sensor and tactile display.

As described above, the discriminability index is calculated separately for each of the tactile sensor, tactile display, entire system, and human perception. Finally, by comparing these indices, the bottleneck in the system can be identified.

4 Outline of Roughness Transmission System

The proposed evaluation method is applied to a tactile-roughness transmission system (Okamoto et al. 2009), which is outlined here. The roughness transmission system consists of a master-slave-type robot, as shown in Fig. 3. The motion of the slave arm is synchronized with that of the master arm. A tactile sensor is installed on the slave arm. The roughness sensation of a texture scanned by the tactile sensor is transferred to the operator on the master side by using a tactile display. The system can transfer the perceived roughness of gratings with a surface wavelength varying 0.8–2.0 mm in increments of 0.2 mm.

To deliver the sensation of roughness to a system user, the system transfers vibrotactile stimuli to the finger pad of the user while s/he explores a rough texture using the master-slave system. The vibratory frequency and amplitude of the stimuli are controlled. While scanning the texture, the displacement applied to the finger pad is determined by

$$y(t) = A(t) \sin (2\pi \frac{x(t)}{\lambda(t)}) \tag{11}$$

where $x(t)$ and $\lambda(t)$ denote the position of the user's finger on the texture along the X-axis and surface wavelength of the texture, respectively. The vibrotactile frequency is determined by $f(t) = |v(t)|/\lambda(t)$, where $v(t)$ is the exploring velocity of the user's finger. The frequency changes according to the hand speed and online-estimated surface wavelength. The tactile sensor estimates $\lambda(t)$, and transfers it to the master side of the system. The amplitude of the vibratory stimuli is given by $A(t)$, which is determined by the magnitude of the sensory outputs of the tactile sensor in real-time. $A(t)$ is not used in this study since the evaluation method is applied to $\lambda(t)$ (see sections 5 (first paragraph) and 5.3.2).

4.1 Tactile Display and Master System

Fig. 4 shows the tactile display used in the system. The display adopts a piezo-stack actuator (NEC/TOKIN, ASB510C801P0, Japan) as a stimulator. The stimulator is installed on a linear slider. The user of the system places his/her right middle finger on the stimulator and then moves his/her hand along the linear guide (X-axis), as shown in Fig. 3. The position of the linear slider is measured by a linear encoder and sent to a control computer for producing the tactile stimuli. The computer outputs the voltage supplies to the stimulator based on $x(t)$, $\lambda(t)$, and $A(t)$, which are determined using (11). As a result, the stimulator produces a displacement along its longitudinal direction (Z-axis). The control frequency for the tactile display is 3 kHz. The participants agreed that the stimuli perceived by the equipment were similar to those perceived when they explored rough textures such as gratings by using a stylus with a blunt tip.

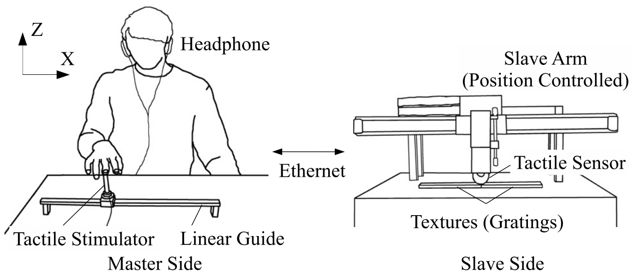

Fig. 3 Master-Slave-type Roughness-transmission System

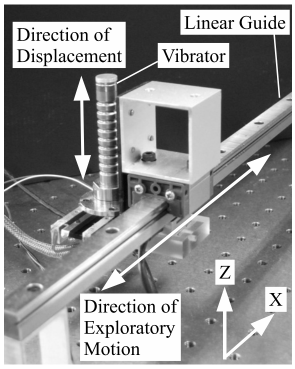

Fig. 4 Tactile Display

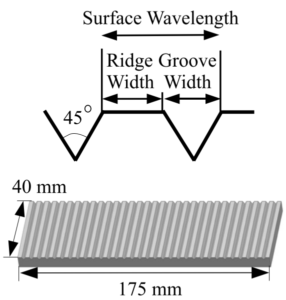

Fig. 5 Grating

4.2 Tactile Sensor and Slave System

The slave system is mainly comprised of a slave arm and tactile sensor. The tactile sensor is installed on the arm, as shown in Fig. 3. The sensor consists of silicone rubber with a Young's modulus that is similar to that of a human finger (Mukaibo et al. 2005). The dimensions of the sensor are three times as large as those of the average human middle finger. Strain gauges are embedded inside the sensor as transducers. When the arm moves and the sensor scans the texture surfaces, the deformation of the tactile sensor is sensed by the strain gauges. The outputs of the strain gauges are sampled at 1 kHz.

The tactile sensor estimates the surface wavelength $\lambda(t)$ of rough textures. $\lambda(t)$ is estimated using the relationship $\lambda(t) = |v(t)|/f(t)$, where $f(t)$ denotes the vibratory frequency of the sensory outputs at t. $f(t)$ is acquired by computing the short-time Fourier transformation (STFT) of the sensory outputs. The estimation algorithm is described in detail in the literature (Okamoto et al. 2009).

Fig. 5 shows the grating scanned by the tactile sensor. The grating has alternating machined grooves and ridges on its surface. Its surface wavelength is characterized by the sum of the groove and ridge widths. In our study, the ratio of the groove width to the ridge width was 1, i.e., the groove width is equal to the ridge width.

5 Application of Proposed Method to Roughness Transmission System

As an example, the proposed evaluation method was applied to a roughness transmission system; the performance is described here. The evaluation was conducted following the procedures described in section 3.2. As described in section 3, the proposed method assesses the transmission capability of a unique physical quantity. The roughness transmission system functions by transferring two types of physical quantities: $\lambda(t)$ and $A(t)$. The proposed method was applied to $\lambda(t)$; therefore, $A(t)$ was not transferred in the experiments. In normal usage, $A(t)$ determines the amplitude of the vibrotactile stimuli in proportion to the magnitude of the sensory outputs of tactile sensor in real-time. However, instead of using $A(t)$, the amplitude of the vibrotactile stimuli was determined here by an equal sensation curve of the vibrotactile stimuli such that the amplitude does not affect the participants' perception. This is elaborated upon in section 5.3.2. Since λ is more appropriate for discrimination rather than signal detection tasks, the tasks in the experiments were designed to be the former.

5.1 Evaluation of Tactile Sensor

An experiment was conducted to estimate λ of gratings using the tactile sensor. In the experiments, the sensor scanned the gratings, and STFT was computed from the sensory outputs acquired there. The scanning velocity was sinusoidal with a frequency of 1.07 Hz and maximum speed of 197.0 mm/s; the speed and frequency were determined by the average measured data in literature (Okamoto et al. 2009), in which thirteen people explored a virtual texture with the same tactile display used in this study. The computation for the estimation was conducted at 1 kHz and was based on the data for five cycles, i.e., 4.665 s. Fig. 6 shows the experimental results as the average and standard deviation of the estimated $\lambda(t)$.

The data shown in Fig. 6 can be used to obtain d' by applying the law of comparative judgment (Thurstone 1927). The concept is as follows. We have two probabilistic variables X_1 and X_2 that are subject to the normal distributions $N(\mu_1, \sigma_1^2)$ and $N(\mu_2, \sigma_2^2)$, respectively. We want to calculate probability $P(X_1 > X_2)$ in which X_1 becomes larger than X_2. $P(X_1 > X_2)$ is equal to $P(X_1 - X_2 > 0)$. The difference between the two variables, $X_{12} = X_1 - X_2$ is also subject to the normal distribution $N(\mu_1 - \mu_2, \sigma_1^2 - 2\gamma_{12}\sigma_1\sigma_2 + \sigma_2^2)$, where γ_{12} is a correlation coefficient between X_1 and X_2, and $\gamma_{12} = 0$ in this case. d' between these two distributions is given by

$$d'_{12} = \frac{\mu_1 - \mu_2}{\sqrt{\sigma_1^2 + \sigma_2^2}}. \quad (12)$$

We regarded $\lambda(t)$ estimated by the sensor as probabilistic variables that are subject to the normal distribution. The mean and standard deviation of the distributions were determined from the data shown in Fig. 6. For instance, when $\lambda = 1.5$ mm, the mean and standard deviation of the estimated values were 1.361 ± 0.169 mm. Furthermore, when $\lambda = 1.0$ mm, they were 0.956 ± 0.255 mm. Thus, X_1 and X_2 were regarded as subject to $N(1.361, 0.169^2)$ and $N(0.956, 0.255^2)$, respectively. X_{12} is subject to $N(0.405, 0.306^2)$. d'_{12} between X_1 and X_2 is $0.405/0.306 = 1.32$. For the other pairs of gratings, d' were computed the same way and are shown in Table 1. By applying the least square method described in section 3.1 on the data of this table, we get the estimated d' as shown in Table 2. $d'_{(0.5,0.5)}$ in the table is meaningless. This variable was merely yielded during the computation of the least square method.

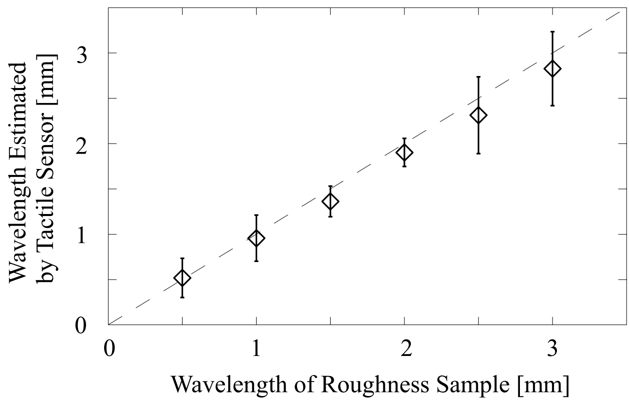

Fig. 6 Surface Wavelengths of Gratings Estimated by Tactile Sensor

Table 1 Tactile sensor: d' between two gratings

		Surface wavelength of sample: λ_1		
		1.0 mm	1.5 mm	2.0 mm
λ_2	0.5 mm	1.31	3.06	5.20
	1.0 mm	-	1.32	3.17
	1.5 mm	-	-	2.35

Table 2 Tactile sensor: Estimated d' between two gratings

$d'_{(0.5,0.5)}$	$d'_{(0.5,1.0)}$	$d'_{(0.5,1.5)}$	$d'_{(0.5,2.0)}$
0	1.60	2.90	5.07

5.2 Evaluation of Tactile Display

The tactile display was evaluated in terms of its ability to accurately present the vibratory frequency. The frequency characteristic of the piezo stimulator reached −3 dB at 310 Hz. The command refresh rate for the stimulator was 3 kHz. The maximum vibrotactile frequency used in the latter experiments was approximately 170 Hz with a supposed maximum hand speed of 200 mm/s and minimum surface wavelength of 1.2 mm. Within the frequency band used in the experiments (up to 170 Hz), in terms of the accuracy of the frequency, the ability for the tactile display exceeds that for human perception, for which the differential limen of vibrotactile frequencies is approximately 20 % over a wide frequency range (Goff 1967; Rothenberg 1977). Thus, we omitted the assessment of the tactile display.

5.3 Evaluation of Human Perception and Entire System

5.3.1 Experimental Methods

Tasks In order to evaluate the transmission capability of the human perception and the entire system, Exps. A and B were conducted. In Exp. A, the participants discriminated pairs of λ by using the tactile display only. λ was given to the control computer of the tactile display instead of being estimated by the slave-side system. Thus, the performance of the tactile sensor did not affect Exp. A. In Exp. B, the participants discriminated pairs of λ using the master-slave system. λ was estimated by the tactile sensor and sent online to the tactile display system.

The experiments were a paired comparison. As shown in Fig. 3, two gratings of different λ were arranged on the left and right side of the linear slider or slave arm as the stimuli. After hearing a beeping sound as a cue, the participants explored both the stimuli for 20 s in total; they then reported the λ that they felt was larger. The task was a two-alternative forced choice. At the beginning of the experiments, the linear guide and slave arm were positioned at the center of their moving range by the experimenters.

Stimuli Four stimuli with λ of 1.2, 1.4, 1.6, and 1.8 mm were used. The interval of each stimulus's λ was set to 0.2 mm. Using the data of preliminary experiments, the interval was determined such that the paired comparison tasks would not become too difficult or easy. The five comparison pairs were obtained by excluding a pair (1.2 mm, 1.8 mm) from the six comparison pairs formed by the four stimuli. The pairs were (1.2 mm, 1.4 mm), (1.2mm, 1.6 mm), (1.4 mm, 1.6 mm), (1.4 mm, 1.8 mm), and (1.6 mm, 1.8 mm). The pair of (1.2 mm, 1.8 mm) was excluded since the participants of the preliminary experiments could correctly discriminate it at a rate of approximately 100%. Each participant performed ten trials per pair for a total of 50 trials. The order of comparison pairs presented to the participants was random. Exps. A and B took approximately 20 and 40 min, respectively, to complete.

Participants Eight paid students from Tohoku University in their twenties participated in both Exps. A and B. Four of the eight participants performed first Exp. A and then Exp. B, while the other participants went in the opposite order. The participants practiced for approximately 5–10 min until they felt familiar with the procedures of the task. The participants wore a headphone and listened to pink noise during the experiments in order to block the sounds produced by the vibrator. Since they had to know the position of the linear slider on the guide, they were not blindfolded.

5.3.2 Vibrotactile Stimuli

As mentioned in the first paragraph of section 5, the transmission system did not transfer the amplitude of the vibrotactile stimuli $A(t)$ in the experiments, while the system usually transfers both $A(t)$ and $\lambda(t)$ in real-time. The amplitude of the stimuli was set to have a constant sensation level such that the amplitude would not affect the judgment of $\lambda(t)$. Hence, the participants judged $\lambda(t)$ solely from the vibratory frequency of the stimuli. The amplitude was determined by obtaining a curve of equal sensation magnitude for vibrotactile stimuli. Before the main experiments, the curve of the equal sensation magnitude for vibrotactile stimuli was identified by a preliminary experiment involving six participants. The preliminary experiment was conducted by the method of adjustment using the same setup used in this study. Fig. 7 shows the identified curve. The vertical axis in the figure is half of the peak-to-peak amplitude of the applied voltage. The error bar in the figure shows the maximum and minimum values of the participants' answers. The corresponding peak-to-peak displacements of vibrations are shown in parentheses in micrometers. The curve was U-shaped with a local minimum around 200–300 Hz. These characteristics are identical to those of the curve of equal sensation magnitude reported in other studies (Goff 1967; Verrillo 1969).The curve is an approximation of the reported values ($R^2 = 0.998$), and it is

$$\begin{cases} \log_{10} a(f) = 3.07e^{-5} f^2 - 1.65e^{-2} f + 2.386 & \text{if } f \geq 35.1 \\ a(f) = 70 & \text{otherwise,} \end{cases} \quad (13)$$

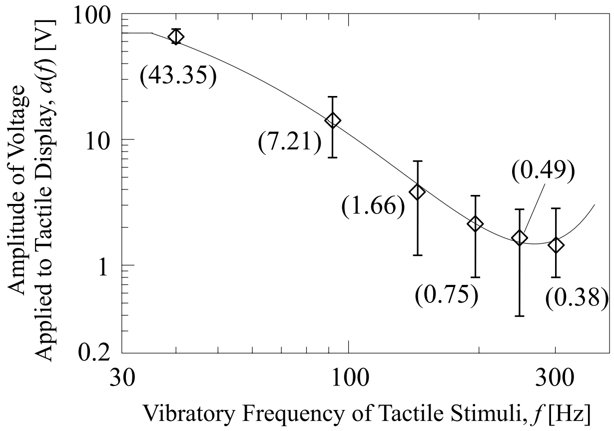

Fig. 7 Amplitude of voltage applied to vibrator based on equal sensation curve. Values in parentheses are the corresponding peak-to-peak output displacement in micrometers.

Table 3 Result of Experiment A (human + tactile display): discrimination ratio for surface wavelengths

		Surface wavelength of samples: λ_1		
		1.4 mm	1.6 mm	1.8 mm
λ_2	1.2 mm	0.82 ± 0.14	0.94 ± 0.05	-
	1.4 mm	-	0.81 ± 0.18	0.90 ± 0.10
	1.6 mm	-	-	0.77 ± 0.16

Table 4 d' for Experiment A (human + tactile display)

		Surface wavelength of samples: λ_1		
		1.4 mm	1.6 mm	1.8 mm
λ_2	1.2 mm	0.93	1.55	-
	1.4 mm	-	0.89	1.29
	1.6 mm	-	-	0.72

Table 5 Estimated d' for Experiment A (human + tactile display)

$d'_{(1.2,1.2)}$	$d'_{(1.2,1.4)}$	$d'_{(1.2,1.6)}$	$d'_{(1.2,1.8)}$
0	0.75	1.50	2.25

where f is the frequency of vibrotactile stimuli. Based on the identified curve, the amplitude of the voltage supply to the vibrator was determined. Hence, in the experiments, the amplitude of the voltage supply was

$$E(t) = a(f(t)) \sin (2\pi \frac{x(t)}{\lambda(t)}) \tag{14}$$

where $f(t) = |v(t)|/\lambda(t)$. The amplitude was set to a constant value when $f(t)$ was smaller than 35.1 Hz so that the voltage supply did not exceed the voltage capacity of the vibrator.

5.4 Results and Estimated d'

The results of Exp. A is given in Table 3. The table shows the ratios at which the participants correctly responded to the pairs of (λ_1, λ_2). The ratios are the averages and standard deviations for the responses of the eight participants. Table 4 presents d' values computed by the averages of the discrimination ratios in Table 3. These d' values were computed into estimated d' values by using the least square method. The estimated d' values are in Table 5.

Table 6 Result of Experiment B (entire system): Discrimination ratio for surface wavelengths

		Surface wavelength of samples: λ_1		
		1.4 mm	1.6 mm	1.8 mm
λ_2	1.2 mm	0.76 ± 0.13	0.84 ± 0.17	-
	1.4 mm	-	0.74 ± 0.24	0.86 ± 0.09
	1.6 mm	-	-	0.79 ± 0.12

Table 7 d' for Experiment B (entire system)

		Surface wavelength of samples: λ_1		
		1.4 mm	1.6 mm	1.8 mm
λ_2	1.2 mm	0.71	0.98	-
	1.4 mm	-	0.64	1.09
	1.6 mm	-	-	0.80

Table 8 Estimated d' for Experiment B (entire system)

$d'_{(1.2,1.2)}$	$d'_{(1.2,1.4)}$	$d'_{(1.2,1.6)}$	$d'_{(1.2,1.8)}$
0	0.57	1.15	1.72

Table 6 shows the discrimination ratios acquired by Exp. B. The corresponding d' values and estimated d' values by the least square method are presented in Tables 7 and 8, respectively.

Fig. 8 shows the estimated d' of Tables 2, 5 and 8. The estimated d' were approximated by a linear equation. In order for the three lines to have the same origin for visual clarity, the scores were shifted such that the y-intercept of each line became zero. The higher the slopes of the lines, the higher is the system's ability to discriminate λ.

5.5 Comparison of System's Transmission Capability

Table 9 summarizes the slopes of the approximated lines. The highest slope was for the human perception plus tactile display at 3.75. The second-highest slope was for the tactile sensor at 3.31. The slope of the entire system was 2.86, which is lower than that of each component. Therefore, the capability of the entire system was limited by the tactile sensor's ability to estimate λ. The results indicate that in order to improve the capability of the entire system, the tactile sensor or its sensing algorithm should be improved first.

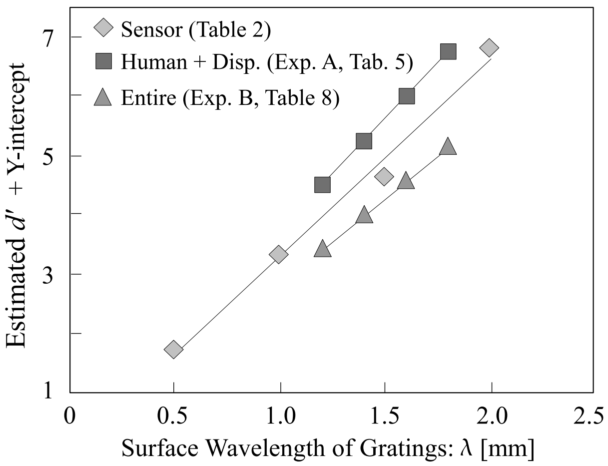

Fig. 8 Graphs of d' vs. Surface Wavelengths of Roughness Samples

Table 9 Slope of d' for Each System

System	Human + Display (Exp. A)	Sensor	Entire (Exp. B)
Slope	3.75	3.31	2.86

5.6 Discussion

In the comparison, the performance of the entire system was worse than that of the tactile sensor and tactile display. Intuitively, the performance of the entire system should be as bad as the component with the worst performance in the system. Here, we discuss why the entire system performed worse than its components due to the propagation of errors.

In the tactile transmission system, the tactile sensor estimates a physical quantity and transmits it to the master-side system with the error. In the master-side system, the tactile display presents the physical quantity to the users of the system. The internal response of the users toward the physical quantity presented by the tactile display includes uncertainty or probabilistic error. Thus, the error of the tactile sensor is additionally imposed onto the perceptual process of the users. Suppose, the tactile sensor estimates the physical quantity with the standard deviation of σ_s. The uncertainty of the human internal response toward the input of physical quantity is expressed as σ_h. The uncertainty of the human response toward the physical quantity estimated by the tactile sensor is $(\sigma_s^2 + \sigma_h^2)^{\frac{1}{2}}$, which is larger than σ_s or σ_h. Therefore, the entire system's ability to discriminate the physical quantity is worse than that of the tactile sensor or tactile display.

According to this concept, the discriminability index of the entire system per unit surface wavelength is determined by

$$d_{s+h} = \frac{1}{\sqrt{\frac{1}{d_s^2} + \frac{1}{d_h^2}}} = \frac{1}{\sqrt{\frac{1}{3.31^2} + \frac{1}{3.75^2}}} = 2.48 \qquad (15)$$

where, d_s and d_h are the slopes of discriminability indices for the tactile sensor and tactile display, respectively. However, the slope of the entire system was 2.86 in the experiment, which showed a better performance than the slope of 2.48. Although the reason of this discrepancy is unclear, we suggest that this increase in the performance was due to the imbalanced effects of d_s and d_h on the human perceptual process. For example, in (15), it would be necessary to weight d_s and d_h in some way for better estimation of the entire system's performance than that expected based on the propagation of errors.

6 Conclusions

In this study, a method for identifying the bottleneck in tactile transmission systems was developed. Such evaluation methods have not been proposed thus far partly because the tactile sensor, tactile display, and perceptual ability of humans have different performance criteria, and their performances cannot be directly compared. This problem was solved by using the discriminability indices as the evaluation criteria. The probabilistic outputs of tactile sensors and humans probabilistic responses in signal detection or stimuli discrimination tasks can be converted into discriminability indices. Hence, the evaluation method that we developed allows us to quantitatively compare the tactile sensor, tactile display, and human perceptual abilities in terms of the transmission capability of physical stimuli. The developed method was applied to a tactile-roughness transmission system, and its ability to transfer the surface wavelength of rough textures was evaluated. The results from the application of the method indicate that the performance of the entire system was limited by the tactile sensor's ability to estimate the surface wavelength.

Acknowledgements This work was supported by grants from MIC SCOPE (082102006,) and MEXT Kakenhi (19360120) and (07J01804).

References

1. Dev P, Harris D, Gutierrez D, Shah A, Senger S (2002) End-to-end performance measurement of internet based medical applications. In: Proceedings the 2002 American Medical Informatics Association Annual Symposium pp, 205–209

2. Fan FE, Culjat MO, King C, Franco ML, Boryk R, Bisley JW, Dutson E, Grundfest WS (2008) A haptic feedback system for lower-limb prostheses. IEEE Transactions of Neural Systems and Rehabilitation Engineering 16(3):270–277
3. Goethals P, Lintermans H, Sette MM, Reynaerts D, Brussel HV (2008) Powerful compact tactile display with microhydraulic actuators. In: Proceedings of the EuroHaptics 2008 pp, 447–457
4. Goff GD (1967) Differential discrimination of frequency of cutaneous mechanical vibration. Journal of Experimental Psychology 74(2):294–299
5. Green DM, Swets JA (1966) Signal Detection Theory and Psychophysics. Wiley, New York
6. Hikichi K, Yasuda Y, Fukuda A, Sezaki K (2006) The effect of network delay on remote calligraphic teaching with haptic interfaces. In: Proceedings of the 5th workshop on network & system support for games 2006 no 12
7. Howe RD, Peine WJ, Kontarinis DA, Son JS (1995) Remote palpation technology. IEEE Engineering in Medicine and Biology 14(3):318–323
8. International Telecommunication Union (2004) Subjective assessment of sound quality. ITU-R Recommendation BS.562-3
9. International Telecommunication Union (2009) Methodology for the subjective assessment of the quality of television pictures. ITU-R Recommendation BT.500-12
10. Jones LA, Lederman SJ (2006) Human hand function. Oxford University Press, Oxford
11. Killebrew JH, Bensmaa SJ, Dammann JF, Denchev P, Hsiao SS, Craig JC, Johnson (2007) A dense array stimulator to generate arbitrary spatio-temporal tactile stimuli. Journal of Neuroscience Methods 161(1):62–74
12. Kontarinis DA, Howe RD (1995) Tactile display of vibratory information in teleoperation and virtual environments. Presence 4(4):387–402
13. Macmillan NA, Creelman CD (2005) Detection Theory–A User's Guide. Lawrence Erlbaum Associates, Hillsdale
14. Motoo K, Arai F, Fukuda T (2007) Piezoelectric vibration-type tactile sensor using elasticity and viscosity change of structure. IEEE Sensors Journal 7(7):1044–1051
15. Mukaibo Y, Shirado H, Konyo M, Maeno T (2005) Development of a texture sensor emulating the tissue structure and perceptual mechanism of human fingers. In: Proceedings of the 2005 IEEE International Conference on Robotics and Automation pp, 2565–2570
16. Okamoto S, Konyo M, Maeno T, Tadokoro S (2009) Transmission of tactile roughness through master-slave systems. In: Proceedings of the 2009 IEEE International Conference on Robotics and Automation pp, 1467–1472
17. Ottermo MV (2006) Virtual palpation gripper. Dissertation, Norwegian University of Science & Technology
18. Pawluk DTV, Son JS, Wellman PS, Peine WJ, Howe RD (1998) A distributed pressure sensor for biomechanical measurements. Journal of Biomechanical Engineering 120(2):302–305
19. Peine WJ, Wellman PS, Howe RD (1997) Temporal bandwidth requirements for tactile shape displays. In: Proceedings of the Sixth Annual Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, ASME International Mechanical Engineering Congress and Exposition pp, 107–113
20. Rothenberg M, Verrillo RT, Zahorian SA, Brachman ML, Bolanowski Jr. SJ (1977) Vibrotactile Frequency for Encoding a Speech Parameter. Journal Acoustical Society of America, 62(4):1003–1012
21. Shirado H, Maeno T (2005) Modeling of human texture perception for tactile displays and sensors. In: Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems pp, 629–630
22. Summers IR, Chanter CM (2002) A broadband tactile array on the fingertip. Journal of Acoustical Society of America (112)5:2118–2126
23. Thurstone LL (1927) Psychophysical analysis. American Journal of Psychology 38:368–389
24. Verrillo RT, Fraiori AJ, Smith RL (1969) Sensation magnitude of vibrotactile stimuli. Perception & Psychophysics 6:366–372
25. Warwick K, Gasson M, Hutt B, Goodhew I, Kyberd P, Andrews B, Teddy P, Shad A (2003) The application of implant technology for cybernetic systems. Archives of Neurology 60(10):1369–1373
26. Yamamoto A, Nagasawa S, Yamamoto H, Higuchi T (2006) Electrostatic tactile display with thin film slider and its application to tactile telepresentation system. IEEE Transactions on Visualization and Computer Graphics 12(2):168–177
27. Yamauchi T, Okamoto S, Konyo M, Hidaka Y, Maeno T, Tadokoro S (2010) Real-Time Remote Transmission of Multiple Tactile Properties through Master-Slave Robot System. In: Proceedings of the 2010 IEEE International Conference on Robotics and Automation
28. Yao H, Hayward V (2005) A tactile enhancement instrument for minimally invasive surgery. Computer Aided Surgery 10(4):233–239
29. Yoshioka T, Bensmaia SJ, Craig JC, Hsiao SS (2007) Texture Perception through Direct and Indirect Touch: An Analysis of Perceptual Space for Tactile Textures in Two Modes of Exploration. Somatosensory and Motor Research 24(1–2):53–70